Evaluation of the Effect of Uncertainty Expression Method on Material Balance Evaluation for Nuclear Safeguards

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Introduction

- The KINAC has been developing an independent material balance evaluation (MBE) program for national safeguards inspection[1]
- However, the IAEA's uncertainty expression method for MBE has limitations
- Benchmark MBEs were performed using three different uncertainty expression methods and optimized method was identified

Research Overview

Identifying the measurement system of the facility

Calculating the MUF using general ledger and the LII

Calculate the MUF uncertainty (σ_{MUF}) using different uncertainty expression methods and evaluate the σ_{MUF}

Conventional IAEA's method	Modified IAEA's method	ISO standard method (GUM)

$H_0: MUF = 0,\ \text{if } |MUF| \le t_\alpha \sigma_{MUF}$ → Measurement uncertainty (Normal)

$H_1: MUF \ne 0,\ \text{if } |MUF| > t_\alpha \sigma_{MUF}$ → Another sources (Abnormal)

Identifying the optimized uncertainty expression method

Material Unaccounted for (MUF): Difference between the book and measured inventory
List of Inventory Items (LII): List of all items in the facility and its measured information

Benchmark Facility Configuration

- The benchmark **facility** is a **fuel fabrication** process with **2 plants** and **12** key measurement points (**KMPs**)
  - The facility consists of **reconversion**, **pelletizing**, **rod insertion** and **assembling** process
  - **The facility** contains **14,538 items** in **15 strata**

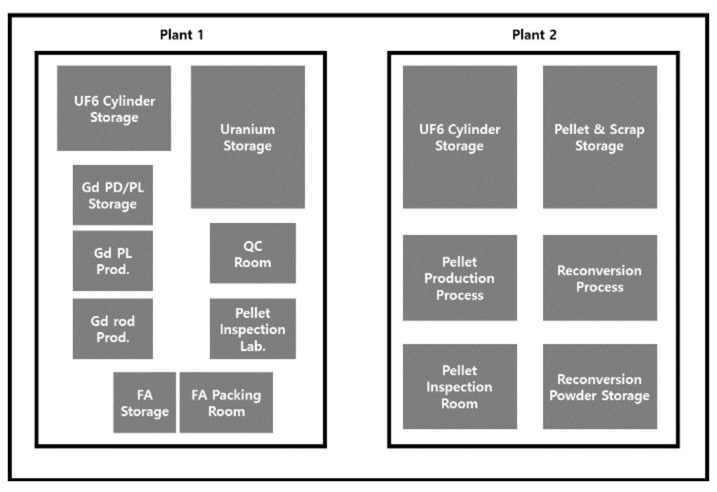

Fig. 1. Facility Configuration

Table 1. KMPs and its description

KMP	Description	Method		
		Weight	U %	wt %
KMP 1	UF_6	EBAL	-	-
KMP 2	Reconversion process			
KMP 3	UO_2 powder		TGA	TIMS
KMP 4	UO_2 green pellet/scrap		-	-
KMP 5	UO_2 pellet/scrap		TGA	TIMS
KMP 6	Uranium nitrate		-	-
KMP 7	Fuel rod			
KMP 8	Fuel assembly			
KMP 9	Scrap (clean/dirty)		TITR	TIMS
KMP 10	Solid waste		-	-
KMP 11	Liquid waste			
KMP 12	Laboratory sample		TITR	TIMS

Table 2. Strata information and measurement system

Stratum	Description	Location	Q	P	T(E)	T(I)
FF-11	Fuel Assembly	FA storage	1	0	0	0
FF-BD	Fuel Assembly (Gd)	FA storage	1	0	0	0
FR-11	Fuel Rod	QC Room	2	0	0	0
FR-11		U storage	3	0	0	0
FR-1G	Fuel rod with Gd	QC Room	2	0	0	0
FR-1G		U storage	3	0	0	0
HE-1L	UF6 Heel	UF6 Cylinder Storage - P1	4	0	0	0
UF-1L	UF6 Cylinder	UF6 Cylinder Storage - P1	4	0	0	0
PD-1L	UO2 Powder	Gd pellet/powder Storage	6	1	1	1
PD-1L		(Re)conversion Process	7	1	1	1
PD-1L		Recon Powder Storage	7	1	1	1
PL1-L	UO2 Pellet(Sintered, pure)	Gd Rod Production Process	9	0	0	0
PL1-L		U storage	3	1	1	2
PL2-L	UO2 Pellet(Sintered) (Gd)	Gd pellet/powder Storage	6	2	2	2
PL2-L		U storage	3	2	2	2
SA-1L	Lab. Sample	QC Room	2	0	3	0
SA-1L		Pellet Inspection Lab. - P1	12	0	3	0
SA-1L		U storage	15	0	3	0
SA-1L		Pellet Inspection Lab. - P2	12	0	3	0
SA-1	Lab. Sample(Fuel rod)	QC Room	2	0	0	0
PM-1L	(Re)conversion Products	U storage	3	0	0	0
PM-1L		(Re)conversion Process	7	0	0	0
SC-1L	Clean Scrap(non-pellet)	Gd Pellet Production Process	12	0	0	0
SC-1L		U storage	3	3	3	3
SC-1L		Pellet & Scrap Storage - P2	7	3	3	3
SC-1L		Pellet Production Process - P2	7	3	3	3
SC-1L		Recon Powder Storage	7	3	3	3
SC-PL	Clean Scrap(Pellet)	Gd pellet/powder Storage	6	3	3	3
SC-PL		U storage	3	3	3	3
SC-PL		Pellet Production Process - P2	7	3	3	3
SC-PL		Pellet & Scrap Storage - P2	7	3	3	3
SD-1L	Dirty Scrap	U storage	3	4	3	4
SD-1L		Recon Powder Storage	7	4	3	4
SD-1L	Liquid Waste	U storage	3	0	0	0

Uncertainty Expression Methods

Methods

Conventional IAEA's method[2,3]

$$V = V_r + V_g + V_s$$

$$V_r = \sum_{k=1}^{K} \overline{wt}_k^2 x_k^2 \left(\frac{\delta_{rq}^2}{n_k m_k} + \frac{\delta_{rp}^2}{r_k m_k} + \frac{\delta_{rt(E)}^2}{c_k r_k m_k} \right)$$

$$V_g = \sum_q^Q \delta_{gq}^2 \sum_i^{n_q} \overline{wt}_{qi}^2 M_{qi}^2 + \sum_p^P \delta_{gp}^2 \sum_i^{n_p} \overline{wt}_{pi}^2 M_{pi}^2 + \sum_{t(E)}^{T(E)} \delta_{gt(E)}^2 \sum_i \overline{wt}_{t(E)i}^2 M_{t(E)i}^2$$

$$V_s = \sum_q^Q \delta_{sq}^2 \overline{wt}_{sq}^2 M_{sq}^2 + \sum_p^P \delta_{sp}^2 \overline{wt}_{sp}^2 M_{sp}^2 + \sum_{t(E)}^{T(E)} \delta_{st(E)}^2 \overline{wt}_{st(E)}^2 M_{st(E)}^2$$

$$V_t^* = V_r^* + V_s^*$$

$$V_r^*(MUF) = \sum_{i=1}^{G} S_i^2 \left(\frac{\delta_{r_i}^2}{r_i} + \frac{\delta_{r(r_i)}^2}{c_i r_i} \right)$$

$$V_s^*(MUF) = \sum_{l=1}^{L} T_l^2 \delta_{st(I)}^2$$

$$V^* = V + V_t^*$$

$$\sigma_{MUF} = \sqrt{V^*}$$

Modified IAEA's method[2,3]

$$V = V_r + V_g + V_s$$

$$V_r(MUF) = \sum_{k=1}^{K} x_k^2 \left(\frac{\delta_{rq}^2}{n_k m_k} + \frac{\delta_{rp}^2}{r_k m_k} + \right.$$
$$\left. \sum_{g(k)=1}^{G(k)} \left(\frac{\delta_{rt(E)}^2}{c_g r_g m_g} + \frac{\delta_{rt(I)}^2}{c_g r_g m_g} \right) \right)$$

$$V_g(MUF) = \sum_q \delta_{gq}^2 \sum_i M_{qi}^2 + \sum_p \delta_{gp}^2 \sum_i M_{pi}^2 + \sum_{t(E)} \delta_{gt(E)}^2 \sum_i M_{t(E)i}^2 + \sum_{t(I)} \delta_{gt(I)}^2 \sum_i M_{t(I)i}^2$$

$$V_s(MUF) = \sum_q \delta_{sq}^2 M_q^2 + \sum_p \delta_{sp}^2 M_p^2 + \sum_{t(E)} \delta_{st(E)}^2 M_{t(E)}^2 + \sum_{t(I)} \delta_{st(I)}^2 M_{t(I)}^2$$

$$\sigma_{MUF} = \sqrt{V}$$

ISO standard method (GUM)[4, 5]

$$X = \sum_{k=1}^{K} \left(\sum_{j(k)=1}^{J(k)} \left(\sum_{i(jk)=1}^{I(jk)} Q_{ijk} \right) \times P_{jk} \times T(E)_{jk} \times T(I)_{jk} \right)$$

$$u(x_{jk})^2 = \left[\sum_{i(jk)=1}^{I(jk)} \left(\frac{\partial x_{jk}}{\partial Q_{i(jk)}} \right)^2 Q_{i(jk)}^2 \right] \delta_q^2 + \left(\frac{\partial x_{jk}}{\partial P_{jk}} \right)^2 P_{jk}^2 \delta_p^2 + \left(\frac{\partial x_{jk}}{\partial T(E)_{jk}} \right)^2 T(E)_{jk}^2 \delta_{t(E)}^2 + \left(\frac{\partial x_{jk}}{\partial T(I)_{jk}} \right)^2 T(I)_{jk}^2 \delta_{t(I)}^2$$

$$u(X)^2 = \sum_{k=1}^{K} \sum_{j(k)=1}^{J(k)} \left(u(x_{jk})^2 \right)$$

$$\sigma_{MUF} = u(X)$$

Process

Conventional IAEA's method
1. Stratification by element
2. Calculate isotope σ_{MUF} from element analysis
3. Stratification by isotope
4. Calculate σ_{MUF} from isotopic measurement
5. Calculate total σ_{MUF}

Modified IAEA's method
1. Stratification by element and sub-stratification by isotope
2. Calculate isotope σ_{MUF} by sub-stratum
3. Calculate total σ_{MUF}

ISO standard method (GUM)
1. Stratification by measurement system
2. Identification of equation to calculate X(=^{235}U) in facility
3. Identification of uncertainty sources for measurements in the equation
4. Calculate the σ_{MUF} for each item, stratum and facility

Results

Conventional IAEA's method

	Meas. Inventory (kg)	Book Inventory (kg)	MUF (kg)	σ(MUF) (kg)	Significance(3σ)
U235 Weight	38,572.800	38,548.731	-24.069	43.546	No

V(MUF,Isotope)	Vr(MUF,Isotope)	Vg(MUF,Isotope)	Vs(MUF,Isotope)
1101.218	790.957	11.677	298.584

Stratum	Vr(xkq)	Vr(xkp)	Vr(xkt(E))	qpt(E)	Vg(q)	Vg(p)	Vg(t(E))	qpt(E)	Vs(q)	Vs(p)	Vs(t(E))
FF-11	0.02684	0.00000	0.00000	1.00000	0.000	0.000	3.543	1.00000	118.958	0.000	0.000
FF-BD	0.13767	0.00000	0.00000	2.00000	0.000	0.000	0.016	2.00000	0.046	0.000	0.000
…											
SD-1L	0.00000	0.00000	0.00000								

V(MUF,Isotope)	Vr*(MUF)	Vs*(MUF)
795.045	762.572	32.473

ID	S_i	Vr*(MUF)
1	42.465	5.861E-03
2	1.866	1.132E-05
3	0.720	1.685E-06
…		
46	244.962	6.002E+02
47	100.477	1.010E+02

t	T_l	Vs*(MUF)
1	5380.966	2.895E+01
2	1843.539	3.399E+00
3	345.439	1.193E-01

Limitations
- Measurement results of the elemental and isotopic analysis is not independent
- Items in the same stratum are not homogeneous
- Inherent limitations from quantifying the systematic error cannot be managed

Modified IAEA's method

	Meas. Inventory (kg)	Book Inventory (kg)	MUF (kg)	σ(MUF) (kg)	Significance(3σ)
U235 Weight	38,572.800	38,548.731	-24.069	33.7730958	No

Stratum	Description	Location(wt%)	q	q(i)	t_E	t_E(i)	p_l	p_l(i)	t_l	t_l(i)
PD-1L	UO2 Powder	PD Storage(1.28)	8	1	1	1	1	1	1	1
		1.6					1	3		
		2					1	5		
		2.2					1	6		
		2.3					1	7		
		2.4					1	8		
		2.9					1	10		
		3.15					1	12		
		3.45					1	13		
		4					1	17		
		4.1					1	18		
		4.5					1	20		
		4.65					1	21		

u(MUF,Element) (kg)	V(MUF,Element) (kg2)	Vr(MUF)	Vg(MUF)	Vs(MUF)
33.773	1140.622	793.839	29.349	317.433

Stratum	Vr(xkq)	Vr(xkp)	Vr(xkt(E))	qpt(E)	Vg(q)	Vg(p)	Vg(t(E))	qpt(E)	Vs(q)	Vs(p)	Vs(t(E))
FF-11	0.02684	0.00000	0.00000	1.00000	0.000	0.000	3.543	1.00000	118.958	0.000	0.000
…											
PD-1L	0.00817	0.99476	0.02072	13.00000	0.000			13.00000	0.000		
PL1-L	0.00002	0.00000	0.00000	14.00000	0.000			14.00000	0.000		
PL1-L	0.00134	0.57481	0.01198	15.00000	0.000			15.00000	0.000		
PL2-L	0.00000	0.00017	0.00000								
PL2-L	0.00005	0.01307	0.00027								
SA-1L	0.00000	0.00000	0.00000								
SA-1L	0.00000	0.00000	0.00000								
SA-1L	0.00000	0.00000	0.00000								
SA-1L	0.00000	0.00000	0.00000								
SA-1	0.00000	0.00000	0.00000								
PM-1L	0.00000	0.00000	0.00000								
PM-1L	0.00860	0.00000	0.00000								
SC-1L	0.00001	0.00000	0.00000								
SC-1L	0.00022	46.98033	0.15660								
SC-1L	0.00013	7.26356	0.02421								
SC-1L	0.00004	0.53546	0.00178								
SC-1L	0.00001	0.06580	0.00022								
SC-PL	0.00000	0.01033	0.00003								
SC-PL	0.00025	31.77216	0.10591								
PL1-L	0.00000	0.00458	0.00002								
PL1-L	0.00012	0.01420	0.00118								
SD-1L	0.00009	600.06381	0.02000								
SD-1L	0.00003	100.95828	0.00337								
SD-1L	0.00000	0.00000	0.00000								

Limitations
- Measurement results of the elemental and isotopic analysis is not independent
- Items in the same sub-stratum are not homogeneous
- Inherent limitations from quantifying the systematic error cannot be managed

ISO standard method (GUM)

	Meas Inventory (kg)	Book Inventory (kg)	MUF (kg)	σ(MUF) (kg)	Significance(3σ)
U235 Weight (KG):	38,572.800	38,548.731	-24.069	13.717	No

Q	P	T(E)	T(I)	Total U235	V(235U)
6	1	1	1	42.465	0.007

KMP	Plant	Location	MDC	Batch Name	Cont. No	Qty	ULot No	Gross (KG)	Net (KG)	Uran (%)	Uran (KG)	U235 (%)	U235 (KG)
C	Plant 1	Powder Sto	GQRC	L16	8LM220	1	HO-16N20	474.9	327.1	87.804	287.207	2.214	6.359
C	Plant 1	Powder Sto	GQRC	L16	8LM220	1	HO-16N20	476	326	87.804	286.241	2.214	6.337
C	Plant 1	Powder Sto	GQRC	L16	8LM220	1	HO-16N20	381	232	87.804	203.705	2.214	4.510
C	Plant 1	Powder Sto	GQRC	L16	8LM220	1	HO-16N20	476.7	324.5	87.804	284.924	2.214	6.308
…													
C	Plant 1	Powder Sto	GQRC	L16	8LM220	1	HO-16N20	473.2	323.2	87.804	283.837	2.231	6.332
C	Plant 1	Powder Sto	GQRC	L16	8LM220	1	HO-16N20	471	319	87.804	280.149	2.231	6.250

Stratum	V*(MUF) (kg^2)	Stratum	V*(MUF) (kg^2)
FF-11	0.062	PL1-L	20.724
FF-BD	0.282	PL2-L	0.233
FR-11	0.014	SA-1L	0.000
FR-1G	0.002	SA-1	0.000
HE-1L	0.000	PM-1L	0.017
UF-1L	2.434	SC-1L	5.439
PD-1L	6.067	SC-PL	9.591
		SD-1L	143.284

Limitations
- The quality of the facilities' measurement system has to be managed with the documented standard processes
- Realistic uncertainty of the GUM method for DA is much bigger than the ITV

Conclusion

- The **three uncertainty expression methods** (conventional·modified IAEA's method and ISO standard method) **have limitations** and the **limitations of one method is the advantages of the other methods**
- The MBE program will **adopt ISO standard method** since the **IAEA's methods** limitations **cannot be managed**

References

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